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2003 PEER REVIEW

of the U.S. Department of Energy Photovoltaics Subprogram

September 30, 2003

Peer Review Panel:

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Dr. Neal Anderson
Dr. Sheila Bailey
Dr. Gary Cheek
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Mr. Richard Moorer
Deputy Assistant Secretary of Energy
For Technology Development
U.S. Department of Energy
1000 Independence Ave., SW
Washington, DC 20005

Dear Mr. Moorer:

We, the members of the 2003 Department of Energy Photovoltaic Subprogram Peer Review panel, are pleased to submit the results of our review of the program in the attached document. As a panel we offer our thanks and appreciation to the program staff and participants who went to such effort to provide the panel with the information it needed to conduct this review. It was a pleasure to work with such an outstanding group of professionals. The signatures of the panelists below signify our consensus on the findings and recommendations included in the report.

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Executive Summary

The Thin Film Partnership and Systems Reliability research efforts examined during this review are outstanding accomplishments for DOE that are emblematic of the high standards and exceptional capabilities that the panel found during the peer review of the entire program in 2001. The focus on individual projects in this peer review and the constructive criticism offered by the panel are meant to strengthen an already strong program. In an industry that is growing and changing as quickly as photovoltaics (PV), needs and priorities have to be constantly reassessed. In addition to observations concerning specific projects, the panel also identified common concerns that impact the overall program.

The National Renewable Energy Laboratory (NREL) and Sandia play a central role in the research projects reviewed, coordinated through the National Center for Photovoltaics (NCPV). NREL plays a lead role in the thin film projects and Sandia focused on the systems and reliability research efforts reviewed by the panel. The role of the laboratories in the projects reviewed has been outstanding in terms of quality of science, technology and engineering; relevance to national needs and DOE mission; and programmatic performance, management and planning. The panel's only concerns are with the challenges DOE faces in sustaining their laboratory capability.

Equipment and facilities are aging and failing at the laboratories, and at universities. Funds for personnel and current research are being cannibalized to sustain equipment that should have been replaced long ago. The PV subprogram needs the proposed Science and Technology Facility as soon as possible, along with a separate, substantial capital equipment budget to upgrade current equipment in order to continue the high quality work performed by the laboratories and universities.

DOE also needs a strategy and new resources to attract and retain the quality personnel that have been instrumental in the subprogram's success. The first wave of PV researchers is starting to retire, but there is little room in the budget to hire their replacements before they leave so that they can pass on their institutional knowledge. At Sandia, growing demand for their technical expertise in systems research and reliability has overwhelmed their budget and personnel. They are stretched to the limit, yet up until last year their budget had been stagnant for a decade. Experienced personnel are attracted to other areas of the lab where budgets are growing and they have greater research opportunities. At universities, promising graduate students pursue research in solar energy, only to find that the industry is still too young to offer more than a few positions, and the national laboratories have few openings because their budgets are limited as well. An exceptional research capability at both Sandia and NREL is at risk in the immediate future unless DOE develops a strategy for dealing with these ongoing strains on the subprogram's talent.

Overall, DOE's thin films research effort is outstanding. DOE is the only institution supporting research across the spectrum of thin film technologies at a time when other countries and many individual companies have retreated. Research has generally been very high quality and productive.

Sustaining DOE photovoltaic research is important to addressing growing foreign competition for future PV markets. Japan's share of total PV shipments has grown from 21% to 49% since 1995. Europe's share of total world shipments has held steady between 22% and 26% over the same period. But U.S. shipments have declined from 45% to 20% market share. In the face of aggressive domestic market development programs in Japan and Germany, the base of PV manufacturing in the U.S. is in jeopardy. The technical excellence of the DOE PV research subprogram is one of the key advantages that is keeping existing U.S. manufacturing here, and is building a base for future growth. With PV shipments averaging 35% annual growth over the last five years, it is important for DOE research to help companies with U.S. manufacturing remain competitive in a market with enormous growth potential.

Thin films in particular are at a critical juncture as companies are moving to large-scale manufacturing and face significant challenges in reaching commercial viability and competitiveness in this rapidly expanding market. Crystalline and polycrystalline silicon PV products that compete with thin films dominate the market today. They have improved in both cost and performance. Although these materials also face challenges in sustaining the recent pace of improvement, research is ongoing into reducing silicon feedstock costs, minimizing material losses, reducing energy input and enhancing device performance.

The rationale for developing thin film photovoltaics remains valid – they still have high potential for very low material requirements leading to low material costs; for large-scale, low-cost production; for flexibility and low weight that give an advantage in building-integration and other applications; and for competitive performance. The fact that competing materials have continued to improve does not reduce the advantages of thin films, but DOE should consider whether some thin film issues may need greater attention in light of competition from other materials and the challenging transition thin films are making from laboratory to production. While impressive small area thin film efficiencies have been realized, a significant, persistent efficiency gap continues to exist between that of large modules and champion small area efficiencies. An urgent priority of the DOE program should be to understand the materials, device and other factors that are the cause of this gap and to develop creative solutions that eliminate this bottleneck. Reliability is an equal cause for concern.

Because thin films are entering their window of opportunity for commercialization, all of the Thin Film Partnership participants should be concerned with these obstacles. The Institute for Energy Conversion (IEC) and NREL possess the requisite materials and device characterization techniques and skills necessary to understand these problems and create the needed processing and device structure solutions. The efficiency gap and reliability issues should be an urgent priority for these organizations working in collaboration with industry partners.

Thin film companies face enormous investments in large-scale manufacturing facilities that have never been built at the scales necessary to achieve cost-competitiveness. There has been a contraction in the number of firms involved in thin films. For example, BP Solar has exited from thin films development and the Thin Film partnerships. DOE's research support plays a critical role in helping to reduce some of the risk involved, and this work should continue. However, as the current generation of thin film materials progress, DOE should also consider new directions for the thin film partnerships that would incorporate other technology paths. The approach embodied in the Thin Film Partnerships could be very effective for materials beyond amorphous silicon, copper-indium-diselenide and cadmium telluride.

Specific observations and recommendations on individual projects included in the body of the peer review report are summarized here, by project/presentation.

- NREL's technical support of the Thin Film Partnerships is outstanding in all categories. Funds that support NREL's work is money well-spent and the nation should invest in the personnel, equipment and facilities needed to sustain this national resource.

- Overall, the Thin Film Partnerships effort has been outstanding in the quality of science, technology and engineering and in its relevance to national needs and DOE's mission. Management of the partnerships overall is excellent to outstanding. The effort could benefit from updating its near- and mid-term program assumptions, objectives and goals with a systematic analysis of technical, economic and market conditions for thin films.

- In thin silicon research the panel rated the work by Energy Photovoltaics (EPV) as good to excellent in science, technology and engineering. Relevance to national needs and DOE mission was excellent and the management and organization of their work was excellent to outstanding. The project had clear objectives and a clear approach to accomplishing them. AstroPower's research was good to excellent in all categories. The panel's main concern focused on the viability of the ceramic substrate AstroPower is developing and their assumptions concerning energy balances.

- In cadmium telluride research the panel rated First Solar's research as excellent in all areas. It was very clear that DOE funding and technical expertise had enormous beneficial impacts on First Solar, and that their plans and technical objectives were on a solid footing. However, their targets for efficiency and plans for manufacturing appear to be very ambitious given the challenges facing cadmium telluride.

- In copper-indium-diselenide (CIS) research the panel reviewed projects involving Shell Solar, Global Solar, EPV and International Solar Electric Technology (ISET).

    - The quality of science, technology and engineering for this project was rated good to excellent. Shell Solar has made impressive strides in research and in transitioning to manufacturing in the past. However, their current research objectives appeared to focus on very practical engineering issues that are not as challenging. The work's relevance to national needs and DOE's mission is excellent. Program planning and management were good, but could be improved by laying out clear intermediate research steps to accomplish long-term goals for CIS.

    - Global Solar received good to excellent ratings in all areas, and was notable for its steady contribution to technical publications and innovations in marketing and product introduction.

    - ISET was rated excellent in all areas. The "PV Paint" approach to deposition they are pursuing is very challenging and risky, but it also has the greatest potential for a significant breakthrough – the kind of high-risk, high-payoff research that government needs to support.

    - EPV's project received good to excellent ratings across the board. The hollow cathode sputtering process is very innovative, and they have obvious strength in developing manufacturing equipment. However, the panel was concerned with how they plan to overcome the basic manufacturing problems facing their product.

- In amorphous silicon research, the United Solar Systems Corporation (USSC) project was rated excellent in all areas. The combination of technical advances and success in manufacturing scale-up may be the only way to accomplish the materials and energy balance, device stability and performance necessary to make amorphous silicon viable. They have a good, reliable, rolled product that is easily installed and have contributed substantially to the entire thin film research effort through extensive publication and collaboration with other amorphous silicon research efforts under the NCPV.

- University research in thin films included amorphous silicon research at Penn State, cadmium telluride research at the University of Toledo, and the broad thin film research support and coordination effort at the University of Delaware, Institute for Energy Conversion (IEC).

    - Penn State's research was simply outstanding, led by some of the most exceptional researchers in the field, Dr. Chris Wronski and Dr. Robert Collins. The only concern is Dr. Wronki's imminent retirement and the shift of key members of his team like Dr. Collins to other institutions. DOE should make every effort to engage them in further research.

    - The University of Toledo's work in cadmium telluride was rated excellent in all areas. They are working on a difficult topic with declining industry support as some companies have abandoned cadmium telluride development. A tighter focus on defining what are the critical problems in cadmium telluride development could make a project that is already a very productive investment even more effective.

    - The IEC was given excellent to outstanding ratings in all areas. The breadth of their capabilities and involvement in every aspect of thin film development was impressive. They are clearly a widely used resource for the partners to obtain measurements, characterization and basic input to their research. The IEC's expertise in devices could help other emerging PV technologies beyond those in the Thin Film Partnerships, and the panel encourages DOE to continue making them accessible to other elements of the PV subprogram.

- In Thin Film module reliability research the panel reviewed work conducted by the Florida Solar Energy Center (FSEC) and by NREL. The FSEC project received excellent to outstanding ratings. This work is critical to helping thin film products enter the market by identifying and avoiding module failures that could damage the reputation of thin film products. The targeted materials characterization and examination of failure mechanisms conducted by FSEC gets at the root causes of module failures. The work led by Tom McMahon was given outstanding ratings in all areas. In a difficult research area, this work is breaking new ground, yielding clear results and producing a high return on investment. It deserves a high priority for sustained support.

- All of the systems research and reliability efforts presented at the review were rated as outstanding in all areas. This work is absolutely essential to making thin films and other emerging PV technologies take off in the market. The level of detail, attention to targets and goals, and the impact they have on the industry and PV development shows this effort is focused and organized. The panel was very concerned that the resources to implement this effort are stretched to the limit. Module reliability research, outreach and training of installers are all critically important and there should not be "borrowing" from one area to sustain another. Systems research and reliability issues need more resources at FSEC, at the Southwest Technology Development Institute (SWTDI) and in inverter research. All of the projects were also exceptional for their emphasis on transferring their knowledge to others and creating solutions that others can implement – they have an exit strategy for accomplishing their objectives and moving on to new challenges.

- The work at FSEC is an outstanding element of DOE's PV subprogram that researches PV performance in the field. Their focus on whole system performance and on problems and issues that make a difference to consumers is exactly right. So is their work in developing codes, standards and practices that work for PV deployment and not against it. FSEC has managed to become a national resource providing expertise and assistance all over the country.

- SWTDI is doing an equally outstanding job as the "hot and dry" climate counterpart to FSEC. The information presented on causes of system failure and the high proportion arising from poor installation was revealing. They have developed clear insights into the barriers PV faces from defects in product design, inhospitable codes and standards, lack of consumer information and poor practices by some installers. They are also making essential contributions to solving these barriers to widespread PV deployment.

- The inverter research at Sandia is outstanding and essential to PV industry development. Inverters are a critical, frequent source of PV system failure and a major contributor to system costs. This research and the collaboration it is fostering with other distributed generation technologies, industry and the national laboratories appears to be a well-planned and well-executed approach to solving the problems with inverters. The panel's main concern is with the future of this effort because of underfunding, deteriorating equipment and lack of a clear succession plan to replace key researchers who are ready to retire.

Introduction

The U.S. Department of Energy conducted an independent peer review of its Photovoltaic (PV) subprogram on August 13-15, 2003 in Golden, Colorado. This was the second peer review of the PV subprogram in two years, following a September 2001 peer review of the entire subprogram. In contrast, this peer review focused on the Thin Film Partnerships (TFP), Thin Film Module Reliability and Systems Research elements of the subprogram. The panel was the same as 2001, except for the addition of Dr. Gerald Caesar as panel chairperson. Panelists, whose names appear below, were selected based on their broad understanding of PV technologies and markets and their independence from direct participation in any of the DOE PV efforts[1]. The panelists were:

- Dr. Gerald Ceasar (Panel Chairperson), Program Manager, Advanced Energy Technologies, Advanced Technology Program, NIST, Gaithersburg, MD
- Dr. Neal Anderson, Associate Professor, Department of Electrical and Computer Engineering, University of Massachusetts, Amherst, MA
- Dr. Sheila Bailey, Lead Scientist, Quantum Dot Solar Cell Technology, Photovoltaic and Space Environments Branch, NASA Glenn Research Center, Cleveland, OH
- Dr. Gary Cheek, Private Consultant to the Semiconductor Industry, Newport Beach, CA
- Dr. George Cody, Scientific Advisor, Exxon Corporate Research (Retired); Currently, Visiting Professor, Dept. of Mechanical & Aerospace Engineering, Rutgers University.
- Dr. Terry Peterson, Manager, Solar Power, Electric Power Research Institute, Palo Alto, CA

In preparation for this Peer Review Meeting the panelists were provided with copies of the U.S. Photovoltaic Industry Roadmap, and the National Photovoltaic Program Plan, 2000 – 2004. They were also given copies of each presentation prior to the review meeting. During the course of the review, the panelists heard presentations from a senior research manager from Sandia National Laboratories (Sandia), two senior research managers from the National Renewable Energy Laboratory (NREL), and 17 principal investigators.[2]

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[1] Panel resumes are included as Appendix C.
[2] A list of presenters and topics is provided in Appendix A.

Unlike the previous peer review, the panel decided not to group responses to projects. Although the Thin Film Partnership projects and the Systems Research projects were closely related and had considerable interaction, the individual projects were distinctly different. The detailed project information provided was specific enough for the panelists to comment on each project. Nevertheless, the panel chose to make observations that related to the whole set of activities. These observations are presented as an introduction to the major topic areas of Thin Film Partnerships, Thin Film Module Reliability, and Systems Research.

The panelists were asked to assess the program on the basis of three criteria:

1.) Quality of the science, technology and engineering.

2.) Relevance to national needs and the DOE mission; and

3.) Programmatic performance, management and planning.

The panelists ranked the program elements using a scale with rankings that included outstanding, excellent, good, marginal, poor and unsatisfactory.[3] These are the same category definitions as in the last peer review, where outstanding had the following definition:

- "Outstanding science, technology and engineering" means world-class R&D that defines the state of the art.
- "Outstanding" with respect to relevance means that the work performed is fundamental to the success of the subprogram, and could not be targeted better within current budget circumstances.
- "Outstanding for program management" indicates that the program is operating as effectively as possible and maximizing its return on investment within its funding constraints.

Review of Program Components

Thin Film Partnerships

The following sections present the panel's observations on the strengths and weaknesses of DOE's individual activities in Thin Film PV research. The discussion follows the order of the presentations at the peer review, starting with information on NREL's technical support to the Thin Film PV partnership provided by Dr. Rommel Nouffi on the first day of the meetings, accompanied by a guided tour of NREL's laboratory facilities. Next Dr. Harin Ullal presented an overview of the entire Thin Film PV Partnership, followed by presentations from industry partners involved in research on Thin Film silicon; copper-indium-diselenide (CIS) and copper-indium-gallium-

[3] The evaluation criteria are included in Appendix B.

selenide (CIGS); cadmium-telluride CdTe; and amorphous silicon. University elements of the program were then presented, starting with work on amorphous silicon at Penn State University, cadmium telluride research at the University of Toledo, and the work of the university Center of Excellence for Thin Film research at the Institute of Energy Conversion , University of Delaware. On the second day information was presented on Thin Film module reliability research at the Florida Solar Energy Center and NREL.

Together these presentations and the supporting material provided to the panelists was a good sampling of all the major activities encompassed by the Thin Film Partnership. This partnership is a government/industry/university program whose aim is to accelerate the development of cost-effective Thin Film technologies. The panel heard from the senior managers of the program at NREL. There were presentations from technology partners whose research focuses on devices and products that are near or emerging into market applications, and from R&D partners who are researching more fundamental Thin Film issues.

Overall, DOE's thin films research effort is outstanding. DOE is the only institution supporting research across the spectrum of thin film technologies at a time when other countries and many individual companies have retreated. Research has generally been very high quality and productive.

Thin films are at a critical juncture as companies are moving to large-scale manufacturing and face significant challenges in reaching commercial viability and competitiveness in a rapidly growing market. Crystalline and polycrystalline silicon PV products that compete with thin films dominate the market today. They have improved in both cost and performance. Although these materials face challenges in sustaining the recent pace of improvement, research is ongoing into reducing silicon feedstock costs, minimizing material losses, reducing energy input and enhancing device performance.

The rationale for developing thin film photovoltaics remains valid – they still have high potential for very low material requirements leading to low material costs; for large-scale, low-cost production; flexibility and low weight that give an advantage in building-integration and other applications; and for competitive performance. The fact that competing materials have continued to improve does not reduce the advantages of thin films, but DOE should consider whether some thin film issues may need greater attention in light of competition from other materials and the challenging transition thin films are making from laboratory to production. While impressive small area thin film efficiencies have been realized, a significant, persistent efficiency gap continues to exist between that of large modules and champion small area efficiencies. An urgent priority of the DOE program should be to understand the materials, device and other factors that are the cause of this gap and to develop creative solutions that eliminate this bottleneck. Reliability is an equal cause for concern.

Because thin films are entering their window of opportunity for commercialization, all of the Thin Film Partnership participants should be concerned with these obstacles. IEC and NREL possess the requisite materials and device characterization techniques and skills necessary to understand this problem and then create the needed processing and device structure solutions. The efficiency gap and reliability issues should be an urgent priority for these organizations working in collaboration with industry partners.

Thin film companies face enormous investments in large-scale manufacturing facilities that have never been built at the scales necessary to achieve cost-competitiveness. There has also been a contraction in the number of firms involved in thin films. For example, BP Solar has exited from thin films development and the Thin Film partnerships. DOE's research support plays a critical role in helping to reduce some of the risk involved, and this work should continue.

However, as the current generation of thin film materials progress, DOE should also consider new directions for the thin film partnerships that would incorporate other technology paths. The approach embodied in the Thin Film Partnerships could be very effective for materials beyond amorphous silicon, copper-indium-diselenide and cadmium telluride.

NREL Technical Support of Thin Film PV Partnership

NREL Technical Support and Lab Tour (Rommel Nouffi, NREL)
The panelists rated NREL's technical support of thin films as outstanding in relevance to national needs and DOE mission, science and engineering, and program management.

The panel considers NREL, its facilities, equipment and personnel a "treasure house" of capability for Thin Film research. Funds that support NREL's capabilities is money well spent, and the nation should invest in the capital equipment and facility upgrades necessary to maintain this capability at its peak. The panel strongly supports the proposed Science and Technology Facility, and funding for the capital equipment needed to fully outfit the new facility as well as bring current NREL facilities up to date. During the tour of NREL and during the course of the presentations the panel heard frequent references to specific equipment and facilities that were:

- Aging and less capable than new equipment.
- failing from lack of maintainability.
- being kept in operation at the expense of funds to support staff patent applications, conferences and publications.

It appears that the operating budget at NREL and Sandia are being partly cannibalized to keep basic equipment operating, equipment that should have been replaced by now. The panel strongly recommends a separate and substantial capital equipment appropriation to halt the erosion in NREL and Sandia's capability and to restore their equipment and facilities to a world-class status that matches the capability of their personnel. It is a shame to see deterioration in their capabilities due to insufficient support. If the capital equipment problem is not resolved quickly without impacting regular operating budgets the panel is concerned that NREL and Sandia may have difficulty in attracting and retaining the young talent that will be needed to replace the first generation of PV researchers, who are now nearing retirement. Tight budgets that trade off operations against capital equipment maintenance do not allow for hiring new talent before key people retire. The best students and researchers also go where the equipment and facilities are state-of-the-art, and they know that the quality of facilities and equipment reflects the priority and stature of an institution. If photovoltaic research is a national priority, then the equipment and facilities devoted to it must reflect that it is a national priority.

The panel noted that NREL is central to all of the Thin Film research activities reviewed – practically every project depends on NREL for measurement, characterization, and technical expertise. NREL has done an outstanding job with the resources available, but there is a concern that they may not be able to keep up the pace without more resources, as thin films and PV technology in general makes the difficult transition to large-scale manufacturing. DOE needs to plan for a transition as staff, equipment and facilities age.

Overview of Thin Film PV Partnership (Harin Ullal – NREL)
The Thin Film partnerships effort has been outstanding in the quality of science, technology and engineering, and in its relevance to national needs and DOE's mission. Its rating for programmatic performance, management and planning was rated as excellent to outstanding. While the long-term goals of the effort are clear and logical, the intermediate goals and milestones necessary to achieve them were less specific. Overall, the partnerships have accomplished impressive improvements in thin films. Six R&D 100 awards is a strong testament to the quality and productivity of the overall partnership. However, there needs to be a more systematic explanation of what the near- and mid-term expectations are for researchers and what will be accomplished with the substantial amount of funds invested in research.

Part of the problem is that information on intermediate milestones was not presented in enough detail, even though the panel suspects that more detail exists. To maintain confidence in its research investments DOE and NREL must make the logic of their research portfolio and the systematic steps involved in its research obvious to everyone. This would also help in explaining adjustments in planning, like the establishment of the reliability team and testing of thin films under field conditions – moves that the panel strongly supports.

The panel also recommends that planning and management explicitly include exit strategies that establish criteria for when DOE should step back from funding research in an area. The reasons could be either success that leads to full commercialization, or reaching a dead-end along a research path, lack of any U.S. manufacturing interest in a technology, or any number of logical reasons. The important thing is to be prepared to change course when it is warranted. This may be difficult because the Thin Film Partnerships include technologies that are at very different stages of technical maturity, but it should be done. DOE has terminated PV research efforts in the past when they failed to perform, and that strengthened the program. Having sunset provisions and exit strategies for current research projects would also strengthen current efforts. If projects are not progressing along a learning curve at an adequate pace, they should be phased out.

Thin Silicon

Thin Silicon (James Rand – AstroPower)

This project was rated good to excellent in terms of the quality of the science, technology and engineering; relevance to national needs; and programmatic performance, management and planning.

In view of their past performance some members of the panel were concerned about AstroPower's ability to produce reliable, efficient devices on a large scale on the ceramic substrate they are targeting. They were particularly concerned that ceramic tape casting on such a large scale is not, to their knowledge, a proven high volume manufacturing process in other applications. AstroPower has already had to abandon their first substrate plans. To their credit, AstroPower and DOE's research revealed the problem with their first substrate and they shifted to a new research path. However, the new substrate approach also appears problematic to the panel.

Another problem is that it is apparent in retrospect that AstroPower has publicly been less than forthcoming about technical issues in its research efforts, which reduces the panel's confidence about AstroPower's predictions for its current research. AstroPower has done extremely well in manufacturing of their traditional PV product, but they have been far less impressive with their research results versus plans.

While the device structure presented appears very promising, the researcher glossed over potential shortcomings in terms of kerf losses, surface roughness, and materials conversion efficiency in the chemical vapor deposition process they are proposing. More details on these issues and AstroPower's solutions would have been helpful. There were also questions concerning AstroPower's overall energy balance. The balance between the amount of energy input to the deposition process versus the expected output of AstroPower's solar cells over their lifetime is a critical issue that deserves more attention. Finally, the panel has serious concerns with AstroPower's ability to survive as a company because of the loss of investor confidence that has recently overcome the company. With some of its top management removed and layoffs in both production and research and development, there is a legitimate concern as to whether they will be able to continue as a Thin Film partner with DOE and live up to their contract commitments. DOE needs to carefully monitor this research project to make sure that research funds are well spent and AstroPower delivers the research it has promised.

Thin Silicon (Yuan-Min Li – EPV)

The panel rated this project good to excellent in science and engineering, excellent in relevance to national needs and DOE mission, and excellent to outstanding in management. This project had very clear objectives and a clear direction. The principal investigator knew what had to be achieved in year one, two and three and had a clear approach. He also recognized critical issues and acknowledged the challenges facing the project, particularly finding ways to avoid cross-contamination when doing multiple deposition layers in a single CVD reactor chamber. The panel is concerned that the problems with this approach may be insurmountable on a production scale, and would recommend increased attention to this problem.

EPV's research approach is straightforward, produces results, and it is typical of research on optimizing Thin Film processing. The research has produced promising results, and there is a clear plan for progressing to the tandem cells that are essential to meeting the performance and efficiency goals. This project still has a long way to go in process controls and scaling up from the small control window they have mastered so far. However, it is worthwhile and productive research, especially in addressing the stability issue with a-Si solar cells.

Cadmium Telluride (CdTe)

CdTe (Rick Powell – First Solar)

First Solar's work was rated as excellent in all categories. As the presenter remarked, this project has benefited greatly from its collaboration in the Thin Film Partnership. It was one of the projects that most clearly showed the critical importance of government support for research and development in topics that involve high risks and long-term commitment that are beyond the means of the private sector alone. First Solar has effectively leveraged DOE funds to build manufacturing capability and a product, which directly addresses DOE's goals and is a huge plus for the program. It was also enlightening to hear that the funding from DOE was less important than the access to knowledge and expertise offered by the Thin Film Partnerships. First Solar needs the expertise from NREL and the university partners – a strong indicator of their value and quality.

First Solar is one of the few remaining companies in the world working on cadmium telluride. While they may be overcome by the challenges in the end, they appear to have a reasonable chance of solving the problems and creating a strong U.S. claim in a very promising PV technology with high potential for mass production. First Solar has very aggressive growth targets, moving from their current status of less than 2 MW of production to 25 MW within 2 more years, with products at 10% efficiency. They have conducted a sound analysis of areas to improve in order to reach these goals, including a clear roadmap for advancing cell efficiencies and reducing cell losses. Their emphasis on accelerated lifetime testing is critical to CdTe because of its perceived stability issues. The field-tests currently underway in Springerville, Arizona will be telling. In manufacturing they are working on quality control and finding the source of the erratic stability and performance of cadmium telluride. Their yield data is promising, and it appears they are on a path to good yields even at 8% to 9%. They deserve credit for reaching fledgling commercial production.

Places where First Solar's approach is lacking are in identifying niche markets where their products can gain a foothold while they are perfecting manufacturing and in articulating an exit strategy that will define when they can become independent of government research support. First Solar also needs to present more detail on why they think their approach will be able to achieve the boosts in efficiency they plan for their products.

Copper Indium Diselenide and Copper Indium Gallium Selenide

CIS (Dale Tarrant – Shell Solar)

This project received good to excellent ratings for science and engineering; excellent ratings in terms of relevance to national needs and DOE mission; and good ratings for management.

This project is promising in view of its high efficiency potential and has made good progress in the past, including a cell efficiency record. However, this presentation failed to adequately describe the innovation that was being developed during the current award period and to rationalize the need for government support. Much of the activity appeared to be standard engineering practice that is normally undertaken during manufacturing development.

The engineering research they did discuss appears to be sound and practical, although controlling breakage and otherwise improving yield is only a part of the challenge facing this product. The main issue is whether it is enough to create a successful product.

In terms of relevance to national needs and DOE mission, CIS is clearly one of the most promising of the Thin Film technologies. However, in terms of costs, performance and stability it faces stiff competition from ribbon silicon, which is ahead of CIS. While crystalline silicon technologies face concerns about the supply and cost of silicon feedstock in the long-term, they still dominate current markets and the products continue to improve. There is also a major project underway to develop $5/kg solar grade silicon feedstock.[4] CIS and the other thin films face a critical challenge in establishing themselves as viable competitors to crystalline silicon over the next few years, while PV manufacturing capacity is still in the early stages of expansion. DOE and companies like Shell have played a critical role in laying the foundation for thin films and bringing them to the verge of viability. This project has an excellent chance of creating that transition, if issues in the planning and performance of the research are addressed.

CIS (Jeff Britt – Global Solar)

This project rates a good to excellent score in all areas. It was particularly noteworthy for Global Solar's thoughtful strategy of introducing selected cells from its production line into high value military and space applications while at the same time using the production line as an experimental test-bed for improving its processes. Global Solar is gaining experience with field performance and introducing customers to the unique characteristics of its product while in the midst of research. The panel has some concern about where Global Solar is heading beyond the $6-$8/W market they are competing in now -- and how they will get there -- but their progress is encouraging. The panel also noted that this project has published regularly and contributed to the overall research effort by sharing information. They appear to be making good progress on process controls, and to have realistic steps to reach their goal of bulk power markets. The funds for this research have been well spent.

The fact that they are not moving to monolithic modules may be a good decision for the short term. Monolithic modules may be an Achilles' heel of thin films because any flaw in the manufacturing process can result in huge material waste. By binning the unflawed portions of their submodules and taking a wafer type approach to modules in much the same way as crystalline-silicon manufacturers, they may have identified important productivity improvements.

Global Solar needs more durability testing and proof that their product is stable and reliable in the field before moving to larger manufacturing. The panel would have liked to see durability reports on the products they have sold into niche markets as an indication of their performance potential.

CIS (Vijay Kapur – ISET)

The panel rated this project as excellent in all areas. While it represents a relatively small investment of $400,000 it has a great deal of potential. This project could produce a major breakthrough in CIS manufacturing if it can truly establish a non-vacuum printing process that is comparable in performance over large areas to more proven deposition methods. There have

[4] New $11.3 million ATP project involving AstroPower, Dow Corning and Crystal Systems with Shell Solar as subcontractor was recently announced to develop "New Routes to Ultra-Low-Cost Solar-Grade Silicon for Renewable Energy Generation".

been other processes – notably xerography – that have also gone through a lengthy process to prove their technology and win the corporate support necessary to become a real product.

ISET is very much a research startup with no capability for manufacturing, but they have a reasonable chance of proving the manufacturing process and eventually providing it to other companies. The Thin Film Partnership may help them make the connections they need for a transition from research to implementation if their technology lives up to its promise. It would be beneficial to help them connect with potential partners when they are ready. PV "paint" deserves attention because it potentially has excellent materials use, attractive deployment characteristics and a cost profile that could have a dramatic impact on the market for PV. Progress has been good to date, and device performance has been reasonable. The panel also supports this project because it represents an important addition to the PV research portfolio -- it is a dramatically different approach that is high-risk, but a promising start-up venture. While the principal investigator's projections may be optimistic, continued support is warranted.

CIS (Alan Delahoy – EPV)
This project received a rating of good to excellent in all categories. The principal investigator demonstrated that they have accomplished a lot with help from DOE and other Thin Film partners. Their current devices look promising, although it is not clear that they are ready to produce them commercially. They also have work to do in overcoming the basic manufacturing problems facing their product.

Some of the panel were concerned that they are producing and selling CIS but have a parallel research effort in thin silicon. Are they really capable, and committed to, a transition to CIS over the long-term? Can they support two technologies? Are they biting off more than they can chew?

Beyond those concerns, the project has some very positive attributes. The hollow cathode sputtering process they have developed is very innovative, and demonstrates their strong expertise in manufacturing equipment. Their work on linear sources is generally very innovative, as is their work in transparent conductive oxides. Manufacturing is obviously an area where their expertise in silicon has crossover benefits for CIS development, since they mainly sell manufacturing equipment. The 9.7% efficiency of their devices is also a solid achievement.

Amorphous Silicon

A -Si (Subhendu Guha – USSC)
This project rated excellent in all areas. They appear ready to go from 4 MW to 25 MW of output on their stainless steel, roll-to-roll process. They have established the tandem junction device and are moving toward triple-junctions. In the 1980s, USSC's parent company Energy Conversion Devices

(ECD) invented microcrystalline-doped layers and now USSC is applying it in their product, both for doped and i layers. This combination of technical advances and manufacturing scale-up may be the only way to get to the combination of stability, materials and energy balance, and performance necessary for amorphous silicon to be a competitive product in the long run.

The stability of their product is good, it is flexible, which offers some unique application advantages, and promises to substantially reduce installation costs in the rooftop and other markets they are targeting. Plus they really do have an output advantage in kWh/kW compared to crystalline silicon because of their product's response to the solar resource.

Tom McMahon also commented on the durability advantages of their breathable package. The fact that this is currently the only Thin Film product that PowerLight will use is an endorsement from the field.

There are also spin-off potentials for USSC's manufacturing research in that GE will be working with ECD to cost-effectively make light-emitting diodes (OLEDs) for lighting applications with the roll-to roll line using organic materials. USSC has also contributed to the field with extensive publication and they have a reputation for working well with universities and making real contributions to basic science.

The panel was concerned about the need for further DOE support. USSC has had a long-term research investment from DOE and appears to have started viable manufacturing with a competitive product. Future funding for USSC (and other more "mature" Thin Film Partnership members) should be based explicitly on continued ability and willingness to solve specific problems that directly serve the program's goals, not just past success and continued availability of DOE funds.

University Thin Film Research

A-Si (Chris Wronski – Penn State)

This project was rated outstanding across the board, especially in the quality of science, technology and engineering. This is fundamental work investigating the multiple causes of instability in amorphous silicon, the physics of the material structures and the causal relationship between these structures and efficiency degradation. Some day these conditions may be controllable by manufacturing processes and device design in order to overcome the stability problems in amorphous silicon. Chris Wronski and Rob Collins are also educating high-quality students who will be the leaders in PV and integrated circuit development in the future. It was very good to see basic studies of Thin Film characteristics that could lead ultimately to significant efficiency advances. This type of work balances and complements DOE's investments in other projects that focus more on devices.

DOE is getting a lot of value and an enormous contribution to the basic knowledge base on amorphous silicon for a modest investment of $340,000. If there is room to expand funding for the Thin Film Partnerships, investments like this should be DOE's first priority for increased support. This is not a criticism of the current overall funding allocation among universities, companies and national laboratories, which appears to be well balanced. Rather, it is a recommendation to seek more funds to advance portions of the program that are truly outstanding.

One concern about this and other university research is capacity. Are the universities attracting and retaining the best students in PV and related disciplines at a rate that will be able to replace the first generation of researchers, who are now near retirement? Chris Wronski will soon retire and it is not clear who will be able to carry on his work at the level he has accomplished. Similarly, it is not clear that the universities have enough graduate students and professors to effectively use new funding if it became available. It would be worthwhile for DOE to determine if there is a looming shortage of qualified researchers, and if something needs to be done to solve the problem.

CdTe (Alvin Compaan – University of Toledo)
This is an excellent research project in all areas that focuses on a difficult topic, cadmium telluride. With the decline in companies investing in cadmium telluride and a limited number of university researchers, cadmium telluride research may be losing critical mass. If cadmium telluride research is to continue it is important to sustain research resources like the University of Toledo. The project could be improved by a tighter focus on defining what are the critical problems to be solved and how the university's research will address them. The rationale for this project was good, but not as compelling or as focused as Penn State's work in amorphous silicon. Progress in handling grain boundary issues seems to be stalled. For $247,000 and a very focused scope, this is a very productive investment and could grow with addition of new staff at University of Toledo and continuing investment to attract more students. Toledo's collaboration with First Solar and the credit First Solar gave them for helping to advance their processes was a good endorsement that shows that their work is relevant, although the panel would have liked to see more detail on how Toledo's work connects to the other partners in CdTe development. With Rob Collins moving to Toledo, this program should explore whether the important scanning ellipsommetry technique that Collins has pioneered can be used to good advantage for polycrystalline Thin Film PV technology.

Center of Excellence (Robert Birkmire – IEC)
This element of the Thin Film Partnership received excellent to outstanding ratings in all areas. The panel was impressed with the breadth of the capabilities and involvement of IEC in every aspect of Thin Film development. Over and over in the research write-ups IEC is referenced as

the source for measurement, characterization, and basic input to research that affects the entire industry. IEC has managed to retain core staff and capabilities and stay relevant to the field, as it has progressed. DOE is getting a good return on its investment. They offer a good blend of both engineering and fundamental science work that helps strengthen and combine contributions from the individual Thin Film projects, which are more tightly focused on particular issues and materials.

One area where IEC could play a strong role is in device technology for new solar materials, particularly in organic solar cell development where the current cadre of researchers lacks device expertise. That area of research seems to be underestimating the challenge in making good devices. So far, they have been hitting closer to 1%-3% device efficiency. IEC could help in organic solar cell development and in nanotechnology, but right now, they are mainly focused on Thin Film PV materials. The panel encourages DOE to continue supporting access to IEC for other PV research areas where their expertise could be valuable.

During the discussions IEC offered some interesting statistics on the number of grad students involved in solar and how many remain involved in solar development. Ideally, the proportion should be higher. There seems to be student enthusiasm, but currently the industry appears too small to absorb all the students that might be interested in continuing in solar development. It is a quandary, and although DOE may not be able to solve the problem completely it would be worth examining and discussing the issue with the PV industry, universities and labs to see if there may be ways to keep more of the best students involved in solar development.

Thin Film Module Reliability Research

The panel encourages expansion of this effort to include funds to purchase and test modules from foreign manufacturers. This would provide valuable information for consumers and help in benchmarking the performance of U.S. products.

Thin Film Module Reliability (Neelkanth Dhere – FSEC)

This project rated excellent to outstanding in all areas, with a particularly high rating in terms of relevance to DOE's mission and goals. It is critically important to apply research like this to make Thin Film products reliable and effective for consumers, before thin films develop a bad reputation in the market. The kind of materials characterization and targeted examination of failure mechanisms FSEC is providing get right at the root causes of stability and reliability problems in Thin Film modules. Failure analysis in the integrated circuit industry is treated as fundamental to yield and to meeting customer needs – they understand exactly how good their products are and what they can deliver to customers. The Thin Film PV industry needs to adopt the same approach, and FSEC is creating that kind of fault analysis capability.

The panel realizes the sensitivity involved in this type of research into the failure mechanisms of commercial products. However, they would encourage DOE and FSEC to reinforce the trend toward greater information sharing among the Thin Film partners and more open discussion of common failure mechanisms. It was reported that the partners are moving in this direction, and the panel believes that greater openness would benefit Thin Film development. The current research approach appears to be very beneficial to individual companies, but considering that all the companies seem to have encapsulation and contact reliability issues it seems counter productive for them to not share more information on these common problems.

Greater openness would also help FSEC to demonstrate more directly the benefits it is delivering to the industry as a whole and to individual companies. Greater openness would certainly provide more opportunities for the University of Florida's graduate students to make their work a part of their studies. The confidentiality requirements involved in their research today makes it practically impossible for a student to base a thesis or paper on the work they do under the program.

Thin Film Module Reliability (Tom McMahon – NREL)
This project is outstanding. The approach outlined by Tom McMahon is very comprehensive and systematic. In a difficult field, his research is breaking new ground, yielding clear results and producing a high return on DOE investment. This group seems to have reached a workable balance between the sensitivity involved in comparing products and investigating how they fail and sharing critical information to help advance all thin films. This project should be given a high priority for sustained support.

Systems Research

Overall, the panel gave the systems research elements of the PV subprogram the highest ratings in all categories -- outstanding. The quality of the science, technology and engineering is outstanding in terms of its impact on the community, creation of new knowledge, and the rate of advances it is producing. This work is critically important to DOE's goals and national needs for creating alternative energy supplies in helping PV devices and systems meet customer expectations – an absolute necessity if PV is ever going to be a widely used energy source. The performance of the program, its management and its planning appears very logical and structured, with clear milestones, schedules and budgets. They have done an exceptional job in managing limited program resources, measuring their performance, and planning for the orderly completion of activities and transition to new projects. They clearly explained and were quite committed to "working themselves out of a job" in areas involving training, certification and standards support that ultimately have to be handled by other institutions.

Overall, systems research is also an area that has been critically under funded. In its last review the panel noted that systems issues would be expanding rapidly because of the growth of the industry and the emergence of new PV technologies into the markets. That has happened, but the recommendation that DOE investment in systems research be expanded to match the growing demand has not. There was a disturbing, common theme in every response to questions about resources and personnel in the systems research area – there are not enough. The capabilities of the research teams cover a very broad area of expertise and are very high quality, but they are only one or two people deep in key positions. Equipment is failing and becoming a bottleneck to research. Facilities are aging and are straining under the growing demand for services from researchers and industry. Key staff members are nearing retirement, and with limited operating budgets that are too often cannibalized to maintain aging equipment, there is no room to hire their future replacements and smoothly transition them into projects before a retirement creates a hole in the team's capabilities. Last year the systems area saw its first increase in funding in nearly a decade, but that seems to only have slowed the rate at which systems research capabilities are falling behind demand. It will take more investment to catch up and sustain this critical element of DOE's research effort.

The PV subprogram has created a balanced portfolio of research in fundamental PV material science, new concepts, thin films, manufacturing, and all elements of cell and module development. Overall, the research is excellent. But research on systems – how all the elements have to be combined to deliver reliable, affordable energy to real consumers – is becoming a gaping hole in an otherwise comprehensive research effort because this element of DOE's research has not been expanded to keep up with the growth and advancement of PV products and markets.

Overview of Systems Reliability Issues and R&D (Charlie Hanley - Sandia)
Outstanding. Systematic testing, data collection and correlation to performance are absolutely essential to making the production of thin films and other emerging PV products take off. This group largely facilitated the growing success of rooftop systems. It is remarkable how they have expanded from crystalline silicon to supporting systems based on thin films in a short period. The work that is being done is not as technically exciting as research into new materials, but it is absolutely critical. The level of detail and attention to targets and goals, and the impacts they will have on the industry and PV development, shows this effort is focused and organized.

At the same time it was also apparent that the resources to implement their plans are stretched to the limit. For example, from discussion with the principal investigators the panel learned that tradeoffs are being made between module reliability research, outreach and training of installers. All three are critically important and there should not be "borrowing" from one area to sustain another – there has to be a better response.

The panel is concerned that Sandia's entire PV effort may be at risk if it gets too small. Losing Sandia and its technical expertise to budget constraints would be a high-risk option. Sandia is particularly vulnerable because it is a multipurpose laboratory. Within the lab personnel have other options besides solar research that are much more well-funded. There has already been migration out of the solar projects at Sandia, and that could accelerate. DOE should examine ways to retain personnel and maintain the capabilities of Sandia. DOE should also consider whether research on PV applications for truck air conditioning is important enough to the Solar program's mission to continue funding, when funds and resources for systems research are so tightly constrained.

Regional Experiment Stations (Jim Dunlop – FSEC)
FSEC provides the "hot and humid" element of DOE's research into PV systems performance in the field, and they are doing an outstanding job. The panel was impressed by their focus on PV as an energy source for the U.S., and therefore on the system as a whole. They are dealing with the practical meat-and-potato issues of fostering the infrastructure support needed by consumers who want reliable installers working with products that perform as they expect, and that can be integrated into systems that are not only safe, but also deliver energy effectively and will be replaced if they do not. It is difficult work on systems that are new and face a myriad of issues in meeting codes, standards and market expectations that were not designed for distributed generation. It is dealing with trying to change or avoid bad rules that can stifle markets before they even have a chance to develop. While the research may never result in an article in Nature or Science, it is most likely to result in PV deployment on a large scale.

Their work is even more important because they and SWTDI are the only ones doing it. This is an area that industry is unlikely to be able to sustain on its own simply because individual companies could never overcome their competition with each other, and they could not be objective. Despite being part of a State of Florida institution and playing a leading role in that state's solar development, FSEC has managed to become a national player providing expertise and assistance all over the country.

Regional Experiment Stations (Andy Rosenthal – SWTDI)
SWTDI is the "hot and dry" counterpart to FSEC, and they are doing an equally outstanding job for the rest of the country. The information they presented on the causes of failure, especially the high proportion of problems arising from poor installation, was revealing. This is real data on the real sources of problems for systems in the field. The pictures and stories of modules sliding off roofs, tangled wiring that should never have passed an electrical inspection, and homeowners who did not even realize their inverters had turned off their expensive PV systems for months dramatically illustrated just how far the PV community needs to go in solving basic systems issues. Their practical work on code issues – pointing out that the current design of

some rooftop systems would not meet the National Electrical Code – and their practical solution of working to change the code because it does not affect safety – showed that they are also making essential contributions to solving the big-picture obstacles to widespread PV deployment.

Inverters (Ward Bower - Sandia)
This work is outstanding and essential to PV industry development. While crystalline silicon modules have 25 year warranties, there are still inverters that fail after one year, that perform so poorly that significant amounts of solar generation are lost before reaching the application, and that represent too high a proportion of system costs. This work is also essential to other distributed generation technologies, and if there is one recommendation from the panel it is to try and expand connections to inverter research supported by fuel cell developers and other distributed generation technologies. The fact that there was a workshop on inverter R&D that included a broad cross-section of organizations, and that the results will become part of an inverter R&D plan, is encouraging. Given the rising competition from foreign manufacturers and growing evidence of problems with inverters in the field, DOE needs to move quickly to determine where research can have the greatest value-added, and how to cope with the weakening position of U.S. inverter manufacturers. The PV community is actually more aware of the intractable problems in improving inverters, and may help developers of other technologies avoid pitfalls.

Competition from European and Japanese inverters is a serious concern – their products are reportedly superior to U.S. offerings and are becoming available in the U.S. If they offer improved performance it will benefit the overall U.S. PV market, but giving up leadership in inverter development may also mean giving up influence on what technology becomes standard in export markets. The panel hopes it will spur competition from U.S. manufacturers to improve their products.

Like other areas of systems research, the team involved in inverter R&D appears stretched to the limit. Last year they received their first budget increase in over 12 years, and they have used it to start a high-performance inverter initiative. That increase should be sustained and if possible expanded.

It is inefficient for critical systems research to be delayed by lack of funds to repair aging equipment that should have been replaced years ago. DOE should seek a separate and substantial capital equipment appropriation to complement its push for a new Science and Technology Facility, and equipment needed for systems research should be high on the priority list.

Personnel and program continuity is a problem that DOE needs to address, particularly in this area. Key staff, including Ward Bower, are near retirement. But resources are too limited to prepare replacements while current staff are still available to train them.

Conclusion

Overall, the PV research projects reviewed by the panel are an outstanding accomplishment for DOE. The PV subprogram is an exceptional and highly unusual partnership that involves industry, universities and national laboratories in a truly collaborative, productive research effort aimed at achieving important national goals. The organization of the program is a model of how to engage industry in research that benefits the public. The National Center for Photovoltaics (NCPV) infrastructure and personnel are essential to sustaining an outstanding, responsive research program. While the panel strongly supports the budget for a new Science and Technology Facility, DOE should seek upgrades to general lab equipment and offices that would strengthen the current infrastructure as well. The subprogram has brought PV from a laboratory novelty and specialized space power source to the verge of providing significant commercial power to consumers. The panel's high opinion of the PV subprogram has not changed since the previous peer review.

The focus on individual projects in this peer review and the constructive criticism and suggestions for improvement offered by the panel are meant to strengthen and reinforce an already strong program. There is always room for improvement, and in dealing with an industry that is growing and changing as rapidly as PV, needs and priorities have to be constantly reassessed. Specific recommendations for improving the program are included in the Executive Summary and in the body of the report.

The panel also recommends changes in the peer review process. The original methodology that involved an open meeting and a broad overview of the entire program and its activities was useful for a peer review of the overall performance of the entire program. As the peer review activity focuses on specific projects there are more issues that involve proprietary or sensitive information that presenters are unwilling to share in a public forum. The panel strongly recommends moving to closed sessions that include only the panel, the principal investigators, and their technical monitors at the National Laboratories. Panelists should sign non-disclosure forms and certify that they have no conflicts of interest.

Along with this transition the panel recommends much more rigorous requirements for the minimum amount of information presenters should provide. Despite templates and instructions, presentations still varied widely in the quality and type of information presented, which makes comparisons and critical review difficult. Some of the presentations lacked information on goals, objectives and innovations that were being developed during the period under review and did not make clear how the DOE PV subprogram was being advanced. Presenters should not only have clear instructions and templates, their materials should also be reviewed and supplemented by their technical monitors to provide consistent information on specific project targets, budgets, tasks, how the project budget fits into the overall PV budget, milestones and activities that have been accomplished and that are planned for the near future, and a clear discussion of research challenges and the approach that will be taken to overcome them. The panel should also consider submitting questions concerning written materials in time for presenters to make improvements to their presentations and deal with major issues before the actual peer review begins. The peer review should also provide an overview of the entire subprogram that explains clearly what elements of the subprogram are being reviewed and how they fit into the overall PV research effort. These recommendations, if implemented, would result in presentations that better reflect the projects the panel is charged with evaluating and would enhance the overall effectiveness of the peer review process.

The peer review process would also benefit from follow-up on the peer review recommendations in the form of a response from DOE on how it did or did not implement recommendations offered in the last peer review in order to provide some feedback to the peer reviewers.

The panel knows that the DOE Energy Efficiency and Renewable Energy Office is creating guidelines for peer reviews; these recommendations should be consistent with those guidelines. The panel has seen similar recommendations implemented in other programs, notably in fuel cell research.

In conclusion, the panel sincerely hopes that this review will help the PV subprogram continue to meet and exceed its current high standards in its future work.

Appendix A: Presenters and Topics (Alphabetical)

Presenters	*Topic*	*Affiliation*
Robert Birkmire	TFP/COE	University of Delaware
Ward Bower	Systems Reliability (Inverters)	Sandia
Jeff Britt	TFP (CIS)	Global Solar
Alvin Compaan	TFP/Universities (CdTe)	University of Toledo
Alan Delahoy	TFP (CIS)	Energy Photovoltaics
Neelkanth Dhere	Thin Film Module Reliability	FSEC
Jim Dunlop	Systems Reliability	FSEC
Subhendu Guha	TFP (a-Si)	United Solar Systems
Charlie Hanley	Systems Research and Reliability	Sandia
Vijay Kapur	TFP (CIS)	ISET
Yuan-Min Li	Thin Silicon	Energy Photovoltaics
Tom McMahon	Thin Film Module Reliability	NREL
Rommel Nouffi	Thin Film PV Partnership (TFPPP)	NREL
Rick Powell	TFP (CdTe)	First Solar
James Rand	TFP (Thin Silicon)	AstroPower
Andy Rosenthal	Systems Reliability	SWTDI
Dale Tarrant	TFP (CIS)	Shell Solar
Harin Ullal	TFP	NREL
Chris Wronski	TFP/Universities (a-Si)	Penn State University

APPENDIX B: EVALUATION CRITERIA

U.S. Department of Energy

Photovoltaics Subprogram 2003 Peer Review

August 13th-15th, 2003
Denver Marriott West - Golden, CO

An evaluation form and a copy of each presentation is included in this binder, in order of their presentation. Please use the forms to enter in your initial rankings and comments for each element of the program. You do not have to respond to each individual sub question – the questions are suggestions for indicators or topics to consider in the overall evaluation. On the last day of the meeting there will be a chance to review and adjust your rankings and comments, and ask any follow-up questions of NREL PV subprogram senior managers before providing your input to the final assessment. The questions are organized into three general areas:

- **Quality of Science, Technology and Engineering:** assess indicators of scientific/technical excellence such as:

  Impact on the scientific community
  Creation of new knowledge
  Technological, engineering or other developments including new technologies that advance research capabilities and reduce costs.

- **Relevance to National Needs and Agency Mission:** Assess impact that the program/project has had, or is likely to have, on meeting the Department of Energy's mission and objectives for alternative energy supply.

- **Programmatic Performance, Management and Planning:** Assess the program/project's ability to meet broad PV subprogram goals. Relevant indicators include:

  Developing and maintaining program plans
  Establishing and meeting scientific and technical milestones, schedules and budgets
  Managing program resources;
  Establishing and implementing program management systems, including performance measurement systems;
  Implementing agreed-upon changes to program baselines;
  Planning for the orderly completion or continuation of programs;
  Documenting the results of programs in scientific and technical reports.

Each question has space for comments, a place to rate the performance of the program element, and an area to add your own notes or observations. The ratings are set to the following scale:

Outstanding
Excellent
Good
Marginal
Poor
Unsatisfactory

Appendix C: Panel Resumes

Dr. Gerald Ceasar, Program Manager, NIST Advanced Technology Program, Electronics and Photonics Technology Office

Gerald Ceasar is a Program Manager for the NIST Advanced Technology Program specializing in ***advanced energy technologies.*** His current areas of responsibility include ***photovoltaics***, ***fuel cells***, ***advanced batteries*** and ***ultracapacitors***, and ***Thin Film large-area electronics***. He has a nascent interest in ***molecular electronics materials*** and ***device technologies*** that look beyond CMOS silicon and that utilize nano- and self-assembly molecular technologies. He joined the Department of Commerce's ATP program in 1994, after a career in industry in a variety of research management and technical positions. At BP Research from 1984-1994, he was manager of the Electronic Materials and Device Laboratory with responsibilities that included amorphous silicon solar cell R&D in the Sovonics joint venture with ECD and electrodeposited thin film cadmium telluride solar cell technology that advanced to commercialization. At ARCO Solar he headed the amorphous silicon R&D group that achieved the world's first 10% a-Si solar cell in 1984. His ten-year tenure at Xerox's Webster Research Center was focused on developing new thin film amorphous silicon and organic photoconductor technologies for copying, electronic imaging, and other large area electronics uses. Prior to his industrial positions, he was an Assistant Professor of Chemistry at the University of Rochester. Dr. Ceasar earned his Ph.D. in physical chemistry from Columbia University and his B.S. degree from Manhattan College. In addition, he has held NSF and NATO postdoctoral fellowships at Cal Tech and at Oxford University in England. He has authored over 90 research papers that have been published or presented at professional meetings and holds several patents.

Neal G. Anderson

Department of Electrical and Computer Engineering
University of Massachusetts at Amherst
Amherst, MA 01003-5110

CURRENT

Associate Professor – Recent research activities in quantum semiconductor heterostructures and their applications in solar cells, lasers, and blue/UV optoelectronics. Current interests include physical information theory and its engineering implications and applications.

EDUCATION

Ph.D. in Electrical Engineering - August, 1988.
North Carolina State University, Raleigh, North Carolina.
Dissertation: "Strained-Layer InGaAs-GaAs Heterojunctions, Quantum Wells and Superlattices: Electronic Structure and Optical Properties" (Chair: Robert Kolbas).

PROFESSIONAL ASSOCIATIONS

•IEEE	• Optical Society of America	• AAAS
• APS	• Philosophy of Science Association	

SELECTED RECENT PUBLICATIONS, PRESENTATIONS AND REPORTS

Neal G. Anderson
"Quantum Channels with Limited Access"
Invited talk presented at the Special Session on Quantum Information Theory: 979th Meeting of the American Mathematical Society, Boston, October 2002. Manuscript in preparation.

Neal G. Anderson
"On Quantum Well Solar Cell Efficiencies"
Invited paper presented at the Workshop on Nanostructures in Photovoltaics, Max Planck Institute, Dresden, Germany, July 30-August 10, 2001.
Published in *Physica E*, 14, 126 (2002).

Sheila Bailey, Neal Anderson, Gary Cheek, George Cody, and Terry Peterson
"2001 Peer Review of the U.S. Department of Energy Photovoltaics Program"
Delivered to Assistant Energy Secretary Robert Dixon on September 14, 2001.
Available through www.nrel.gov/ncpv.

Todd R. Tolliver, Neal G. Anderson, Farid Agahi, and Kei May Lau
"Characteristic Temperature Study of GaAsP-AlGaAs Strained Quantum Well Lasers"
Journal of Applied Physics, 88, 5400 (2000).

Dhrupad A. Trivedi and Neal G. Anderson
"Modeling the Near-Gap Refractive Index Properties of Semiconductor Multiple Quantum Wells and Superlattices"
IEEE Journal of Selected Topics in Quantum Electronics **2**, 197 (1996).

Joan M. Redwing, David A.S. Loeber, Michael A. Tischler, Neal G. Anderson, and J. S. Flynn
"An Optically Pumped GaN-AlGaN Vertical Cavity Surface Emitting Laser"
Applied Physics Letters **69**, 1 (1996).

TEACHING ACTIVITIES

Undergraduate Courses

ENGIN 112	Introduction to Electrical and Computer Engineering
ECE 303	Junior Seminar
ECE 316	Semiconductor Materials and Devices (now ECE 344)
ECE 494	Professional Seminar
ECE 571	Microelectronic Fabrication
ECE 572	Optoelectronics

Graduate Courses

ECE 607	Fundamentals of Solid State Electronics I
ECE 609	Semiconductor Devices
ECE 618	Fundamentals of Solid State Electronics II
ECE 697	Quantum Information Theory
ECE 722	Physical Semiconductor Electronics
ECE 723	Quantum Electronics (formally "Introduction to Masers and Lasers")

List excludes Honors Thesis (ECE 499), Senior Design Project (now ECE 415), and Independent Study (ECE 696)

College of Engineering Outstanding Teaching Award

First recipient of teaching award, established in 1993, given annually to one faculty member in the College of Engineering at UMass.

Biography

Sheila Gayle Bailey

Sheila is a senior physicist in the Photovoltaic and Space Environments Branch at NASA Glenn Research Center. She was the technical lead for "Advanced Concepts" in the Power and On-board Propulsion Technology programs in 2000 and 2001, which gave birth to three new research areas in 2002: Quantum Dot Solar Cell Technology which she currently leads, Solar Arrays and Blankets, and Extended Temperature Solar Cells. Past research has included the texturing of GaAs and InP to enhance light absorption and radiation tolerance in solar cells. This work produced the first V-groove GaAs and InP solar cells. She has authored or co-authored over 110 books, journal and conference publications, 7 book chapters, has two patents and 8 patent disclosures. She is on the Editorial Board of "Progress in Photovoltaics". She is an active member of the American Physical Society and a speaker for the American Institute of Physics Visiting Scientist Program. She is a member of AIAA Aerospace Power Systems technical committee. She has served on the executive committee of the IEEE Photovoltaic Specialist Conference (PVSC) since 1987 and was the Technical Program chair for the 25th PVSC in Washington DC and the U.S. General Chair for the 2nd World Conference in Photovoltaic Energy Conversion in Vienna, Austria in 1998. She will be the General Chair for the 4th World Conference in 2006. She is a member of the Lewis Business and Professional Women and vice president of the Lewis Engineers and Scientists Association. Currently she is an adjunct professor at both the Ohio Aerospace Institute and Baldwin Wallace College and a faculty member of the International Space University. She was recently the co-chair of the Space Systems Analysis and Design Department at the International Space University in Thailand in '99 and Chile in '00. She has a B.S. from Duke University in physics, a M.S. in solid-state physics from the Univ. of N.C. at Chapel Hill, and a Ph.D. in solid-state physics from the University of Manchester in England. She spent a post-doctoral year at the Royal Military College (part of the Univ. of New South Wales) in Canberra; Australia She joined Glenn Research Center in 1985. She is the recipient of the faculty excellence award from Baldwin Wallace College and the Federal Women's Program award. She is an Ohio Academy of Science "Exemplar". She was recently awarded the NASA Exceptional Service Medal for her work in space photovoltaics. She has completed the Office of Personnel Management's Executive Potential Program. She will be inducted into the Ohio Women's Hall of Fame this year at their 25th anniversary celebration in October.

GARY C. CHEEK
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714-742-0785

EDUCATION

Ph.D. in ELECTRICAL ENG, 1983 Katholieke Universiteit Leuven; Belgium
- Graduated Summa Cum Laude
- Thesis: Manufacturing Fundamentals of Polycrystaline Silicon Solar Cells

MASTERS in E.E., 1979, Colorado State University; Fort Collins, CO
- Presented Plenary Session Paper at 15th IEEE International Photovoltaics Conference; the youngest invited speaker in its 36 year history.

B.S. in PHYSICS; 1975: Northern Illinois University; DeKalb Illinois
- Senior Project: Conduction in Chalcogenide Amorphous Glasses

EDITOR: IEEE Transactions on Semiconductor Manufacturing
PROFESSIONAL SOCIETY: Senior Member of the IEEE
TECHNICAL REVIEWER: NSF, several Technical Journals and IEEE Press
TECHNICAL CONSULTANT: U. S. Dept. of Energy, National Renewable Energy Laboratory, DYM, Inc., ASE Americas, Renselar Polytechnic Institute (Yield Course), Medtronic Micro-Rel, IMEC (Belgium)

PROFESSIONAL EXPERIENCE

Magis Networks **San Diego, CA 2003**
Vice-President Operations

Responsible for operations, quality, product engineering and supply chain management for a fabless semiconductor company.

Conexant Systems **Newport Beach, CA 2000-03**
Vice President, Operations and Quality

Responsibilites: Responsible for all Manufacturing, Facilities, Quality, Supply Chain Management, Manufacturing Business Operations and Purchasing. The total spend for COGS is $350M. Responsibilities also include restructuring the business systems, business tools and organization as we transistion to a fabless manufacturing model.

Vice President, External Manufacturing: Responsible for all externally sourced IC manufacturing for both Front end (wafer and Probe) and Back end (Assembly and Test). Approximately 8-10 front end foundries are currently being utilized and about 6-8 back end foundries are qualified. Technologies range from Deep sub-micron digital logic (0.09 um) to larger feature size mixed signal and RF technologies. I am also responsible for the Asia-Pacific Supply Chain.

WaferTech / TSMC **Camas, WA 1999-2000**
Director of Customer Engineering, Business Operations

Responsibilities: Develop and build a customer engineering group and a customer service group to provide engineering support in the areas of new product tapeout, fab operations and logisitics. This work includes the development of a design support group particularly for fabless customers. The Business Operations role includes P&L responsibility for the site through the analysis of GM for each product by technology, evaluation of corporate standards and determination of a favorable technology mix relative to profit goals, customer requirements and equipment utilization.

Analog Devices, Inc. Wilmington, MA, Ireland, Belgium **1983-99**

Foundry Engineering Manager	1992/99
Yield Integration Manager	1991/92
Fab Engineering Manager	1988/91
Operations Analyst	1987
Senior Development Engineer	1983/87

Responsibilities and Competencies of most recent position: Engineering, manufacturing and business responsibilities of running >$25M/month IC supply chain in external (Japan, Taiwan, Singapore, Korea, Israel, South Africa, United States) wafer fab foundries (capacity rationalization, contract negotiation, yield, design interface, costing negotiations, second sourcing, conformance audits, documentation systems, quality and reliability). Technologies include 0.18 um-Digital CMOS, 0.25 um SRAM and mixed signal technologies (double poly capacitors, resistors, silicide, epi and quad metal) 0.18 thru 1.2 um geometries. Supporting and defending corporate litigation issues i.e. Lemelson.

Work in previous positions has included: Sub-um Analog BiCMOS, High Performance Bipolar and Linear CMOS technologies, Process Engineering, Defect Characterization, Technology Transfer, Novel Materials/Technology Development, Analysis of Worldwide Manufacturing Operations, Worldwide SPC Implementation (Team leader), CIM system implementation, Development of Critical Area Yield Models and Cost Driven Manufacturing Analysis Tools (Developer), support to Japan, Korea, Taiwan and Singapore sales and marketing operations.

National Renewable Energy Laboratory, Golden, Colorado 1979-80
STAFF SCIENTIST: Advanced Silicon Solar Cell Development, International group in support of worldwide applications of solar PV

PERSONAL EXPERIENCE

KEY ACCOMPLISHMENT: Have developed a national program that enables graduate level design students to utilize state-of-the-art mixed signal process technology for design projects. This work has broadened the scope of electrical engineering education in the U.S. at institutions that include Georgia Tech, RIT, U of Illinois and UC Berkeley.

BUSINESS DEVELOPMENT: Have established a Non-profit organization (Competitive Education Inc.:501 (C) 3 Organization) to enable usable semiconductor manufacturing computer, manufacturing and test equipment to be transferred out of industry into the university environment.

PUBLICATIONS

EDITOR

- IEEE Transactions on Semiconductor Manufacturing, 1994-1997

THESIS

- Ph.D. Thesis: "**Fabrication of Low Cost Polycrystalline Silicon Solar Cells**", Katholieke Universiteit, Leuven, Belgium, 1984
- M.S. E.E. Thesis: "**Fabrication and Characterization of Indium-Tin Oxide (ITO) / Polycrystalline Silicon Solar Cells**", Colorado State University, 1979

CHAPTER IN BOOK

- Gary Cheek and Geoff O'Donoghue, **Functional Yield Modeling** (Chapter) in *Integrated Circuit Manufacturing: The Art of Process and Design Integration*, Edited by Jose Pineda de Gyvez, IEEE Press, 1998

PATENTS

- G. Cheek and G. O'Donoghue, "**A Bit Stream Approach to Yield Data Analysis**", US Patent Number 4,328,945 (1996)

JOURNAL PUBLICATIONS

- Fabrication and Characterization of ITO on Polycrystalline Silicon Solar Cells, G. Cheek et. al. Applied Physics Letters, Vol. 33 No. 1 (1978), 643-645
- Advances in the Fabrication and Characterization of ITO/Silicon Solar Cells, G. Cheek et. al., Solid State Technology, Vol. 23 No. 2 (1980), 102-108
- Antireflection Properties of Indium Tin Oxide (ITO) / Silicon Solar Cells, G. Cheek et. al., Applied Physics Letters, Vol. 35 No. 7 (1980) 495-497
- Molybdenum Trioxide (MoO3)/Silicon Photodiodes, C. Osterwald, G. Cheek et. al. Applied Physics Letters, Vol. 35 No. 10, 775-776
- MIS and SIS Solar Cells on Polycrystalline Silicon, G. Cheek and R. Mertens, Solar Cells, Vol. 1, No. 3 (1979/1980), 405-420
- The Effective Lifetime in Semicrystalline Silicon, S.C. Jain, R. Janssens, G. Cheek et. al. Solar Cells, 9, (1983), 345-352
- Thick Film Metallization for Solar Cell Applications, G. Cheek et. al. IEEE Transactions on Electron Devices: Special Issue on Photovoltaics, Vol. ED-31, No. 5 (1984), 602-6095

George D.Cody

Scientific Advisor, Exxon Corporate Research, Retired
Currently Visiting Professor Dept. Mech.& Aerospace Engineering, Rutgers Univ.

Dr. George D. Cody received his undergraduate degree from Harvard in Physics in 1952 (AB Summa Cum Laude) and his Ph. D. from Harvard in Solid State Physics in 1957. In 1958 he held a John Parker Fellowship from Harvard and spent that year at the Clarendon Laboratory of Oxford University.

From 1958-1976 he was employed at RCA's David Sarnoff Laboratories where he engaged in research in semiconductors, thin films and superconducting materials. He made major technical contributions to two major materials programs in this period: niobium tin superconductors for the fabrication of high field superconducting magnets and Ge-Si semiconductors for thermoelectric power generation, He was the recipient of RCA's David Sarnoff Gold Medal in Science for this work in 1962 and 1964. Dr. Cody is the co-holder of the basic patent for the Ge-Si thermoelectric material that powers the Voyager, Galileo, and Cassini spacecrafts, and with Dr. Benjamin Abeles, he received the Franklin Institute Ballantine medal for the research leading to this invention in 1979. Dr. Cody is a member of the New Jersey Inventor's Hall of Fame.

In 1970, Dr. Cody held a Regents Professorship at the University of California in San Diego at La Jolla, and taught a graduate course on Superconductivity: Phenomena, Theory, and Materials.

From 1970 to 1975, Dr. Cody was Director of the Physical Electronics Laboratory at RCA's David Sarnoff Research Center and had managerial responsibility for a group of 45 scientists engaged in materials and device research in displays, electro-optical components and exploratory systems. In 1975 he initiated a major research program on low cost manufacture of photovoltaic energy systems.

In 1976, Dr. Cody joined Exxon's Corporate Research Laboratory where he engaged in research on the optical properties of thin film amorphous semiconductors, localization of structure-borne sound, and on non-intrusive, quantitative, vibrational probes of two-phase flow within fluidized beds, transfer lines, feed nozzles and bubble columns. He had technical responsibility for Exxon's fundamental research program in thin film solar cells as well as research programs targeted at the information systems programs of Exxon's new business activities. At retirement on 12/31/98, Dr. Cody held the position of Scientific Advisor (Fellow) at Exxon's Corporate Research Laboratory where he was leading a program to extract information from process-generated noise-Process Vibrational Analysis

Dr. Cody has more than 100 publications and 13 patents. He is a Fellow of the American Physical Society, and served as a member of the Board of Editors for the Journal of Applied Physics from 1984-1987. He is a member of the American Institute of Chemical Engineers. He has been a member of the Chemistry Department Visiting Committee of Princeton University, and a member of the Physics Department Visiting Committee of the University of Texas at Austin. He was a member of the Peer Review Panel of the 2001 Peer Review of the U.S. Department of Energy Photovoltaics Program.

Dr. Cody is currently Visiting Professor in the Department of Aerospace and Mechanical Engineering of Rutgers University exploring applications of Process Vibrational Analysis.

Terry Peterson
Manager, Solar Power
Electric Power Research Institute

Experience

Dr. Peterson's professional experience includes over 25 years of research involvement in both government-sponsored and industrial laboratories. He joined EPRI in 1986, has had principal responsibility for EPRI's Thin Film PV research since then, and responsibility for all EPRI solar-power and green-power market research since 1995.

1995 to present, Manager, Solar Power, EPRI

Define and manage university-industry teamed research in partnership with DOE's National Renewable Energy Laboratory (NREL) to advance Thin Film photovoltaic technology, including work on advanced amorphous silicon modules and advanced CIS-alloy materials.

Define and manage research to assist member companies in understanding green-power marketing opportunities to promote development and deployment of renewable energy generation technologies.

Co-organize 8 national green-power marketing conferences, 1996 through 2003. Manage green-power marketing assessments and market potential as well as project viability and feasibility. Manage green-power pricing studies.

Manage EPRI participation in dish-Stirling and Solar II power-tower technology programs.

1989 to 1994, Manager, Thin Film Photovoltaics and Superconducting Magnetic Energy Storage, EPRI

Define and manage university-industry teamed research; establish partnership with NREL to advance Thin Film photovoltaic technology, including advanced amorphous silicon modules and CIS cells.

Manage EPRI portion of DoD-EPRI research project to design and construct 20-MWh Superconducting Magnetic Energy Storage pilot plant.

1986 to 1989, Project Manager, EPRI

Manage university-industry research team to advance Thin Film amorphous silicon photovoltaic technology.

1983 to 1986, Senior Research Engineer, Chevron Research Company

Conduct research on proprietary catalysts for petroleum refining.

1978 to 1983, (Senior) Research Engineer, Chevron Research Company

Conduct research on Thin Film CdS and multijunction III-V compound PV devices using spray-pyrolysis, reactive sputtering, and metallorganic chemical vapor deposition; lead Thin Film device fabrication group in Solar Group.

1976 to 1978, Staff Scientist, U.C. Lawrence Berkeley Laboratory

Secure DOE support for and conduct research on photovoltaic mechanisms in Cd,ZnS/Cu_xS solar cells.

1975, NSF Postdoctoral Fellow, U.C. Lawrence Berkeley Laboratory

Conduct research on photovoltaic mechanisms in Cd,ZnS/CuxS solar cells.

Education & Affiliations:

Doctorate in Materials Science and Engineering at UC Berkeley, 1975
M.S. in Physics at UC Berkeley, 1971
B.S. in Physics at the University of California at San Diego, 1969

Thesis work was on PV mechanisms in copper sulfide/cadmium-zinc sulfide solar cells. He holds two U.S. patents.

Publications:

He is author or co-author of over a dozen peer-reviewed papers and EPRI technical publications, editor of some 20 EPRI reports, co-editor of two books; and he has appeared as a guest lecturer on photovoltaics and renewable energy technologies at UC Berkeley, Stanford University, and other public forums on numerous occasions.